Mon. Not. R. Astron. Soc. **000**, 1–4 (0000) Printed 1 February 2008 (MN LATEX style file v1.4)

Cosmic Microwave Background polarization and the ionization history of the Universe

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Version of 1 February 2008.

ABSTRACT
We point out that polarization measurements as planned for the upcoming PLANCK mission can significantly enhance the accuracy of cosmic parameter estimation compared to the temperature anisotropy spectrum alone. In order to illustrate this, we consider a standard cosmological model and several modifications that adjust one parameter each to fit the recently published Maxima-1 data. While all models produce acceptable fits as far as the power spectrum is concerned, their corresponding polarization spectra differ widely. The strongest differences are expected for a model with delayed recombination, reflecting the fact that polarization measurements are most sensitive to the processes governing the epoch of recombination.

Key words: Polarization – cosmic microwave background — Cosmology:observations — early Universe

Observations of the Cosmic Microwave Background (CMB) are fundamental for our understanding of one of the most important epochs in the early history of the Universe. After a number of successful experiments, among them COBE (Bennett et al. 1996), BOOMERANG (de Bernadis et al. 2000), Maxima-1 (Hanany et al. 2000), CBI (Padin et al. 2001) to mention just a few, much attention is now focused on the estimation of cosmological parameters such as the densities of baryons Ω_b and dark matter Ω_m and cosmological constant Ω_Λ. In addition, preliminar information about the Hubble constant $H_0 = 100h$, the power spectrum of initial adiabatic perturbation, and the ionisation history of the Universe are available.

Fitting the CMB anisotropy power spectrum to the observational BOOMERANG and Maxima-1 data confirms the prediction of the standard inflation scenario that the Universe is flat, i.e. that the total amount of matter and vacuum energy has the critical value – to an accuracy of 10%, $\Omega_b + \Omega_m + \Omega_\Lambda = 1$. However, as was already pointed out by, e.g., Tegmark & Zaldarriaga (2000b); White et al. (2000); Lesgourgues & Peloso (2000), the data furthermore yield a baryon fraction $\Omega_b h^2$ significantly larger than the value expected from standard Big Bang nucleosynthesis (SBBN) supported by He^4 and deuterium mass fraction measurements. These discrepancies stimulate discussion about possible alternatives that either alter SBBN, e.g. by non-vanishing neutrino chemical potentials (Esposito et al. 2001; Mangano et al. 2000), or add additional non-standard parameters to the cosmological model, such as a tilt of the power spectrum (Tegmark & Zaldarriaga 2000a) or secondary ionization of hydrogen (Tegmark & Zaldarriaga 2000b; Schmalzing et al. 2000). All these factors should be taken into account in the reconstruction of the history of the cosmological expansion, and therefore in the development of methods for cosmological parameter estimation for future high precision experiments like MAP and PLANCK.

So far, however, little attention has been paid to a crucial part of the modelling of the CMB anisotropy spectrum – the history of hydrogen and helium recombination at redshift $z \sim 10^3$. The standard model of hydrogen recombination in the baryonic Universe was suggested by (Peebles 1968) and (Zel'dovich et al. 1968) and generalized to the dark matter models by (Zabotin & Naselsky 1982) and (Jones & Wyse 1985). A more precise model of recombina-

tion taking into account He^4 was developed by (Seager et al. 1999). Recently, in order to test the sensitivity of methods and experiments to the detailed ionization history around recombination, this standard model of recombination has been modified in various ways (Avelino et al. 2000; Battye et al. 2001; Hannested & Scherrer 2001; Landau et al. 2000).

(Peebles et al. 2000) discuss some modification of the primordial ionization history of the hydrogen plasma at $z \sim 10^3$ in the framework of a delayed recombination model, that could arise in certain scenarios with a decaying heavy particle (Sarkar & Cooper 1983; Scott et al. 1991; Ellis et al. 1992; Doroshkevich & Naselsky 2001), primordial black holes evaporation (Naselsky 1978; Naselsky & Polnarev 1987), or cosmic string wakes (Weller et al. 1999). In addition to the 10 cosmological parameters discussed by (Tegmark & Zaldarriaga 2000a) in connection with the CMB anisotropy power spectrum, the possible delay of recombination introduces another one, namely ε_α, related to the production of additional Lyman-α resonance photons in the background of primordial radiation. Their fraction n_α is determined by the simple equation $\frac{\mathrm{d}n_\alpha}{dt} = \varepsilon_\alpha H(t) n_H$, where $H(t)$ is the Hubble parameter and n_H is the neutral hydrogen concentration. The influence of such additional Lyman-α photons on the rate of ionization is fairly straightforward. In comparison to standard recombination, they compensate for the decrease in the number of resonance quanta due to cosmological expansion and lead to an increase of the fraction of ionization, which becomes larger with the ε_α parameter. This process increases the dissipation length for initial adiabatic perturbations and therefore suppresses the secondary Doppler-peaks. It also shifts the anisotropy power spectrum toward lower ℓ by increasing the acoustic horizon at last scattering. Together, the above-mentioned effects lead to significant alterations of the CMB temperature anisotrpy spectrum. However, an even more pronounced effect can in principle be seen in the CMB polarization power spectrum, which is more sensitive to the width of the last scattering surface. Therefore, measurements of the CMB polarization could be a critical test for investigation of the ionization history of the Universe.

There is one additional reason to discuss the possible transformations of the CMB polarization power spectrum due to a more complicated ionization history of the Universe at the period $z \sim 10^3$ and at the later epochs: In (Schmalzing et al. 2000) it was discussed how a "conventional" cosmological model (in particular, with $\Omega_b h^2 = 0.019$ as deduced from SBBN, $\Omega_m \simeq 0.3$ resulting from this and the observed baryonic fraction in clusters of galaxies and standard recombination) can fit the Maxima-1 data provided that the universe reionized at redshifts $z_{\rm re} \sim 15 - 20$ corresponding to electron scattering optical depths $\tau \sim 0.1 - 0.2$. This effect is illustrated in Figure 1 which shows the angular power spectrum C_ℓ of various models as well as the Maxima-1 data taken from Hanany et al. (2000) (the Boomerang and CBI data are also shown, however we shall in this paper adopt the approach of Schmalzing et al. (2000) and fit to the Maxima-1 data only – as was discussed in Schmalzing et al. (2000) very similar results are obtained by fitting to the combined Boomerang+Maxima-1 data of Jaffe et al. (2000)). It is seen that a COBE-normalized,"conventional" model with $\Omega_b h^2 = 0.019$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\tau = 0$ and other parameters given in table 1 tends to lie above the observational data of the Maxima-1 experiment (at least for $\ell \gtrsim 50$). Using the offset lognormal approach of Knox et al. (1998) and Bond et al. (2000) we find a χ^2 of 20.2 for 10 degrees of freedom allowing this model to be rejected with more than 95% confidence. The effect of reionization is to suppress the primary anisotropies (the angular power spectrum) at $\ell \gtrsim 50$ compared to COBE scales ($\ell \simeq 10$) due to electron scattering. A model with $z_{\rm re} = 15$ and all other parameters remaining unchanged is also shown in Figure 1. It is clear that this model provides a considerably better fit to the data ($\chi^2 = 9.8$) - this fact was used by Schmalzing et al. (2000) to argue that under certain simplifying assumptions the Maxima-1 data can be used to place a lower limit on the redshift of reionization $z_{re} > 15$ (8) at the 68% (95%) confidence level. On the other hand, a $z_{\rm re}$ much larger than 10-15 is probably not likely, at least in the framework of current CDM structure formation scenarios - see, e.g., Haiman & Loeb (1998) (although reionization initially must be patchy, their work also indicates that the approximation of a sharp transition of the ionization state of the universe from almost neutral to fully ionized used in our models should be a reasonable first approximation).

Even keeping $\Omega_b h^2$ and Ω_m fixed and assuming standard recombination there are, however, (at least) two alternative ways of suppressing the anisotropy power spectrum C_ℓ at $\ell \gtrsim 50$: either by including tensor modes (gravitational waves) or by assuming a "red-tilted" initial power spectrum (and in both cases $\tau = 0$). These models are also shown in Figure 1 - the additional parameter of the models has been determined by requiring that the amplitude of the angular power spectrum at the first acoustic peak (at $\ell \sim 200$) is the same as that of the model with reionization at $z_{\rm re} = 15$, described above. The additional parameter is given in table 1 for the two models and, as can be seen from Figure 1, both models result in respectable fits to the data (with $\chi^2 = 9.5$ and 6.8, respectively).

One potential way of distinguishing between the above three types of well fitting models is by using observations of polarization anisotropies. The polarization power spectrum for all models discussed above is shown in Figure 2. The most notable difference between the reionization model and the others is the small "bump" at $\ell \sim 5$, which is clearly seen, when the power-spectra are plotted on a logarithmic scale. However, in the displayed linear plot the bump is not seen and it is so small ($< 1\mu\mathrm{K}^2$) that it is unlikely that any of the currently planned experiments (including the PLANCK mission) will be able to test the existence of such a feature.

We now turn to the delayed recombination models*. We adjust the free parameter ε_α by normalizing to the $z_{\rm re} = 15$ model at the first Doppler peak, as above. As seen from Figure 1, the model provides a good fit to the Maxima-1 data ($\chi^2 = 6.8$) and agrees with the recent CBI data point published by Padin et al. (2001) at the range $\ell \sim 1000 - 1500$. In Figures 2 and 3 we show the predicted polarization power spectrum and temperature-polarization cross correlation power spectrum for the various models on

* In order to calculate numerical spectra for the Peebles et al. (2000) models, we generalize the RECFAST code from Seager et al. (1999) and the CMBFAST code from Seljak & Zaldarriaga (1996) to incorporate the additional parameters.

model	parameter	value	$\chi^2_{\rm Maxima}$
Standard	–	–	20.17
Late reionization	$z_{\rm re}$	15	9.77
Tensor modes	$Q_{\rm T}/Q_{\rm S}$	0.15	9.52
Tilted initial spectrum	n	0.95	6.79
Delayed recombination	ε_α	7	6.75

Table 1. χ^2 values for comparing the Maxima data to several variations of a standard cosmological model. All models share the parameters $\Omega_b h^2 = 0.019$, $\Omega_\Lambda = 0.7$, and $h = 0.65$. There is neither a contribution from space curvature ($\Omega_K = 0$), nor from hot dark matter ($\Omega_\nu = 0$) in any of the models.

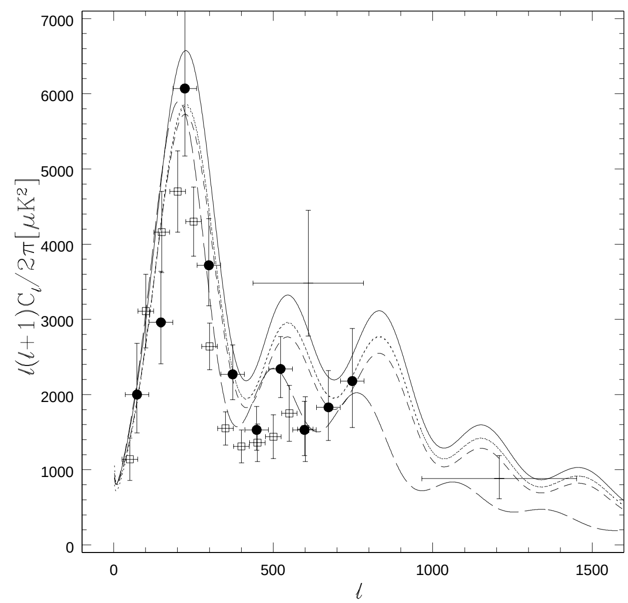

Figure 1. The temperature power spectrum predicted for the various models summarized in Table 1. The lines show predictions obtained with a modified version of CMBFAST. The solid line corresponds to the standard model, while delayed recombination and tilted spectrum are shown in long and short dashed, respectively. Both the model with late reionization and the one including tensor modes shown in dotted lines, because the curves nearly overlap anyway. The various symbols represent data points of the Maxima-1 experiment (solid circles), Boomerang (open squares), and CBI (nothing).

a linear scale. At large ℓ ($\sim 1300 - 1400$) the difference between the late recombination model and all the other models discussed becomes considerable. In fact, it is so large that the forthcoming PLANCK mission is expected to be able to discriminate between the two classes of models. Hence, in this case polarization measurements are expected to add valuable information to the one obtained from temperature anisotropy measurements.

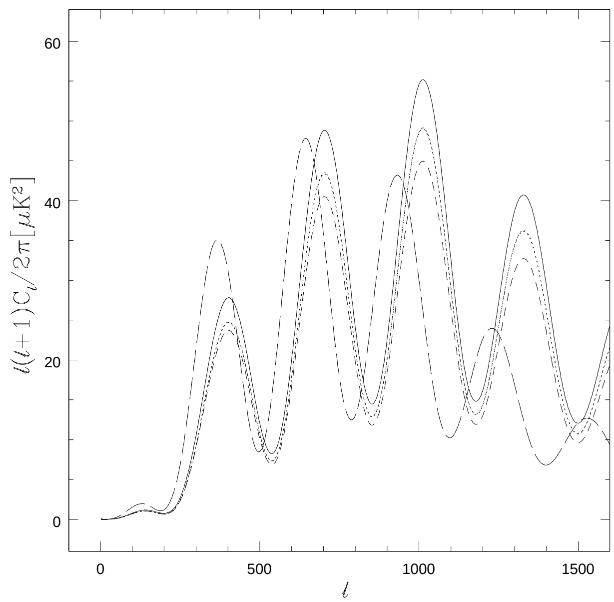

Figure 2. The polarization power spectrum. Line styles are the same as in Figure 1.

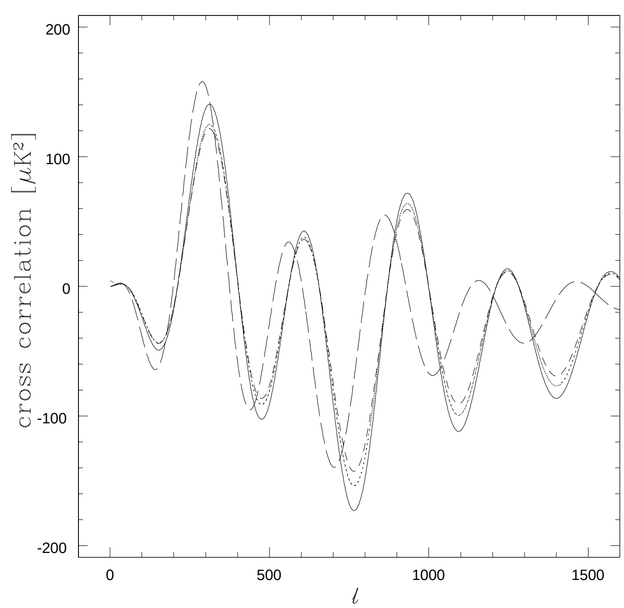

Figure 3. The cross correlation between temperature and polarization. Also here, each model is represented in the same line style as in Figure 1.

ACKNOWLEDGEMENT

We are grateful to J.R. Bond, I.D. Novikov and D. Scott for discussions. This investigation was partly supported by INTAS under grant number 97-1192, by RFFI under grant 17625 and by Danmarks Grundforkskningfond through its support for TAC.

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